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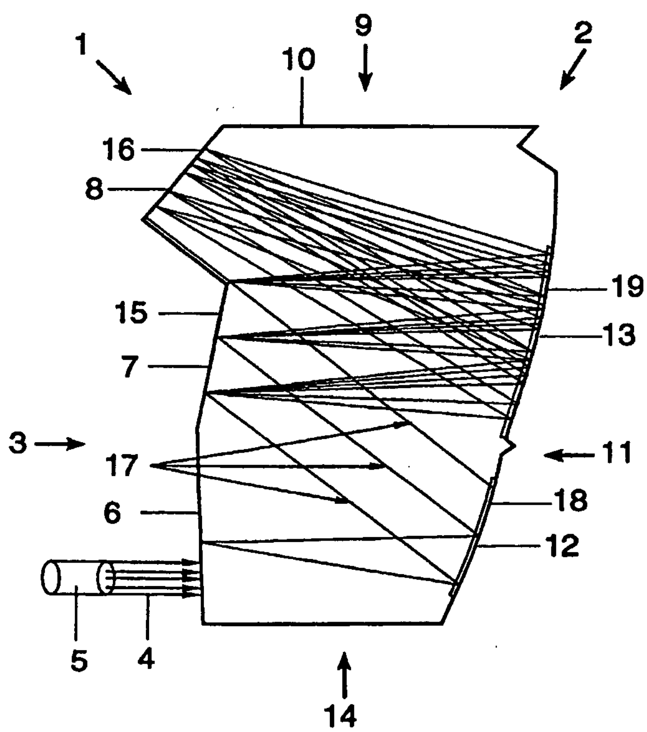
(54) Title: MONOLITHIC SPECTROMETER AND METHOD FOR FABRICATING SAME

(57) Abstract

A monolithic spectrometer (1) is disclosed for use in spectroscopy. The spectrometer is a single body of translucent material (2) with positioned surfaces for transmission (6), reflection (7, 12, 13) and spectral analysis of light rays (8).



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MONOLITHIC SPECTROMETER AND METHOD FOR FABRICATING SAME

The United States Government has rights in this invention pursuant to Contract No. DE-AC05-84OR21400 between the United States Department of Energy and Lockheed Martin Energy Systems, Inc. (formerly Martin Marietta Energy Systems, Inc.). The invention was funded by WFO Interagency Agreement 1855-1662-A1.

FIELD OF THE INVENTION

The present invention relates to spectroscopy, and more particularly to a new and improved spectrometer comprising a single, unitary body of material.

BACKGROUND OF THE INVENTION

The spectrometer, a device with which to analyze light, has been around for about one hundred years. Its usefulness has been extraordinary, and even today its potential uses are increasing. However, the science of spectroscopy to this day is practiced with the use of cumbersome equipment which is comprised of mirrors and lenses and positioning components that are very susceptible to misalignment, distortion, moisture, malfunction and other defects. Today's spectrometer has not been an object of miniaturization as has been other technological machines and equipment because of the lack of technology in making it so. Thus, wider application of the spectrometer has not been possible for areas where miniaturization has become increasingly necessary or preferable. These disadvantages of the modern spectrometer have been overcome with the present invention, both in the invention itself and the method with which it is made.

Regarding the method with which to make the present invention, previous methods utilized in making spectrometers involved optical grinding of lenses such as found in normal optics work. Some breakthrough in the methodology was necessary in order to fabricate the aspheric surfaces, having intersecting surfaces, on the same surface which heretofore represented a major obstacle.

The need to produce aspheric optics as with the monolithic spectrometer in a timely manner and the difficulty in testing these surfaces for accuracy of alignment prompted research in self-aligned and self-contained optical systems. Traditional self-aligned optics have consisted of two coaxial aspheric surfaces, produced in a single machining step with single-point diamond cutting. The present method, developed for the manufacture of the monolithic

spectrometer but applicable for other aspheric surface manufacture, manufactures multiple optical surfaces with intersecting axes in a few machining steps while maintaining a high degree of accuracy heretofore unachieved.

OBJECTS OF THE INVENTION

Accordingly, it is an object of the present invention to provide a new and improved spectrometer. In view of the foregoing disadvantages inherent in known types of spectrometers now present in the prior art, the present invention provides a single, unitary spectrometer which can be used in wider and more novel applications. As such, the general purpose and therefore an object of the invention, which will be described subsequently in greater detail, is to provide a new and improved spectrometer which has many advantages over the prior art and none of the disadvantages.

It is another object of the invention to eliminate the many components of the modern spectrometer and the multiple defects associated with the manufacture, alignment and maintenance of these components.

A further object of the present invention is to miniaturize the spectrometer to sizes that are amenable to wider application.

An even further object of the invention is to provide a spectrometer which can be manufactured more easily and at lower cost.

Still yet another object of the invention is to provide a more accurate spectrometer through finer precision of manufacturing.

And yet another object of the invention is to apply a recently discovered method of machining aspheric surfaces on a single substrate to make the invention with extreme precision.

Further and other objects of the present invention will become apparent from the description contained herein. These together with other objects of the invention, along with the various features of novelty which characterize the invention, are pointed out with particularity in the claims annexed to and forming a part of this application. For a better understanding of the invention, its advantages and the specific objects attained by its use, reference should be made to the accompanying drawings and descriptive matter in which there is illustrated preferred embodiments of the invention.

SUMMARY OF THE INVENTION

In accordance with one aspect of the present invention, the foregoing and other objects are achieved by the spectrometer having a single, unitary body with multiple surfaces and made of a transparent and optically homogeneous material. The surfaces on the spectrometer have a very precise finish and are positioned with respect to each other to permit entry of light rays into the spectrometer and reflection of the same light rays from surface to surface until spectral analysis is made by a detector material on the exiting surface. The spectrometer therefore comprises a single component and eliminates the disadvantages of misalignment and constant realignment, among others, found in the prior art. In addition the spectrometer can be made in miniature sizes to accommodate the needs and novel applications of modern-day spectroscopy.

The unique method utilized in making the present invention possible can be applied again and again to make various sizes and embodiments of monolithic spectrometers as well as be generically applied to produce other similar optical equipment.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

Figure 1 is an isometric view of the spectrometer with the top and front sides facing the viewer.

Figure 2 is an isometric view of the spectrometer with the top and back sides facing the viewer.

Figure 3 is an elevation view of the spectrometer showing the path of the light rays with the front side on the viewer's left and the back side on the viewer's right and with the top side nearest the top of Figure 3.

Figure 4 is a top view of the spectrometer showing the aspheric shapes of the collimating and focusing surfaces.

Figure 5 represents a pictorial sequence of the steps (a through c) of the manufacturing method used in making the monolithic spectrometer.

Figure 6 is a schematic representation of the intersection of the axes of the two aspheric surfaces of the spectrometer.

For a better understanding of the present invention, together with other and further objects, advantages and capabilities thereof, reference is made to the following disclosure and appended claims in connection with the above-described drawings.

DETAILED DESCRIPTION OF THE INVENTION

With reference now to the drawings, and in particular to Figures 1 to 6 thereof, a new and improved spectrometer 1 embodying the principles and concepts of the present invention, and generally designated by the reference numeral 1, will be described in detail.

The spectrometer 1 is a monolithic, unitary body 2 of material. The material is optically homogeneous and transparent so that light may be transmitted therethrough in an unobstructed and unaltered manner. The material may be crystalline, glass, or plastic, depending on the application but is preferably polymethyl methacrylate (PMMA), a man-made acrylic which readily lends itself to the desired characteristics of transparency and resistance to frangibility, but most importantly, ease and susceptibility to the precision fabrication processes of ion-beam milling and diamond-turning machining which makes possible the invention.

The spectrometer 1 may have a multitude of sizes, shapes and forms, but in most preferred instances, the spectrometer 1 will be a solid, rectangular, three-dimensional body 2 with defined surfaces. Figures 1, 2 and 3 show the spectrometer 1 in such a form. The front side 3 is the side from which light rays 4 enter from a light source 5 to be analyzed. The front side 3 comprises at least three distinct surfaces, 6, 7, and 8, each of these surfaces having a separate and distinct optical function. The top side 9 also comprises a distinct surface 10. The back side 11 has two distinct surfaces, 12 and 13, and each of these surfaces has a shape with a specific and distinct optical function. The bottom side 14, as does the top side 10, has no specific optical function and therefore may comprise one of several shapes depending on the application and location desired for the spectrometer.

Describing each of these surfaces in detail now, the entrance surface 6 of the front side 3 has a finish of preferably below 30 angstroms root mean square (RMS). This surface finish is achieved with ion-beam milling or diamond turning precision machining. It is through this entrance surface 6 that light rays 4 to be spectrally analyzed enter the spectrometer 1. This entrance surface 6 is positioned with respect to the other surfaces in order to direct the

entering light rays 4 along a desired path within the spectrometer body 2.

A second surface on the front side 3 of the spectrometer 1 is the grating surface 7. This grating surface 7 has a plurality of very small grooves 15 whose number depends on the application. The preferred embodiment contains several hundred of these grooves 15 per millimeter along the grating surface 7. Other preferred embodiments might have different numbers dependent upon the design factors for specific applications. These grooves 15 are made using either ion-beam milling or diamond turning machining or they may be prefabricated and attached. These grooves 15 perform the function of diffracting the light rays 4, reflected from the collimating surface 12, into the color bands of the light spectrum.

A third surface on the front side 3 of the spectrometer 1 is the imaging surface 8. The purpose of the imaging surface 8 is to retain a detector material 16 with which the light rays 4 exiting the spectrometer 1 onto the imaging surface 8 can be spectrally analyzed. The detector material 16 is typically comprised of germanium or silicon.

The back side 11 of the spectrometer 1 comprises two surfaces, 12 and 13. One is the collimating surface 12 which is adjacent to the bottom side 14. In Figure 4, the collimating surface 12 has an aspheric shape such as that of an ellipse or a parabola. This shape straightens the light rays 4, incoming from the entrance surface 6, into parallel columns 17. The collimating surface 12 is coated with a material 18 such as gold or silver to make it reflective. The finish of the collimating surface 12 is preferably below 30 angstroms root mean square (RMS). The collimating surface 12 is shaped and positioned to receive light rays 4 from the entrance surface 6 and reflect these same light rays 4 to the grating surface 7.

Adjacent to the top surface 10 of the spectrometer 1 and on the back side 11 of the spectrometer 1 is the focusing surface 13. This focusing surface 13 also has an aspheric shape and a coating of reflective material 19. The focusing surface 13 is positioned to receive the diffracted light rays 4 from the grating surface 7 and to reflect and focus these same light rays 4 to the imaging surface 8. The focusing surface 13 is ion-beam milled or diamond turned to a finish of preferably below 30 angstroms root mean square (RMS).

The manner of operation of the spectrometer 1 is as follows. Light rays 4 to be spectrally analyzed enter the spectrometer 1 through the entrance surface 6. These light rays 4 pass through the body 2 and strike the collimating surface 12. The collimating surface 12 straightens these light rays 4 into a column and reflects them onto the grating surface 7. The

grooves of the grating surface 7 diffract these light rays 4 which are reflected onto the focusing surface 13. The focusing surface 13 focuses the light rays 4 onto the imaging surface 8 which analyzes the light rays 4 spectrally with the detector material 16.

The detector material 16 converts the light energy to an electrical impulse whereby the incoming light rays 4 are analyzed as with any spectrometer.

In order for this manner of operation of the spectrometer 1 to be possible, that is, to allow the light rays entering the spectrometer to remain in a straight line while passing through the spectrometer, it is necessary that the center axes of the aspheric collimating surface and the aspheric focusing surface intersect at a common point as shown in Figure 6. For these axes to so intersect at a common point requires a novel method of manufacture. The machining of multiple aspheric surfaces onto separate areas of a common object or piece of material is routinely performed, but the object must be offset with respect to the first surface when a second aspheric surface is machined. This method of manufacture does not permit the intersection of the center axes of the two aspheric surfaces in a predetermined geometric configuration. However, with the new and novel method of manufacture, described below in detail, multiple aspheric surfaces are machined while maintaining a predetermined and desired intersection and geometric configuration of aspheric surface axes. This method represents the preferable, if not only, method to be used in manufacturing the monolithic spectrometer.

Figure 5 pictorially and sequentially portrays the steps (a) through (c) of this unique method of manufacture, which is described in detail as follows. A unitary body or substrate of transparent material is machined, usually by diamond turning precision machining or ion beam milling, into a cylinder 20 of predetermined diameter and parallel ends, 21 and 22, as shown in Figure 5(a). This cylinder 20 is truncated from a diameter on one end [Fig. 5(a)] at a specified angle which is verified as to accuracy. This small, truncated, flat cylinder 20 is then machined on the side opposite the truncation 23 into a hemispherical shape 24 as shown in Figure 5(b). Onto this hemispherical shape 24 is machined the aspherical shape, preferably a parabolic surface, which will become the collimating surface 12 of the monolithic spectrometer. Around this aspheric shape and concentric with it, is machined a cylindrical shape 25 which acts as a positioning shape for the truncated cylindrical 20 in a later step of the method as shown in Figure 5(c). In preparation for machining the second aspheric shape,

which will become the focusing surface 13, the truncated cylinder 20 is tilted onto the truncated side 23 and centered on the machining device with the use of a sphere (not shown) machined from the same material 1 and used solely as a working reference. The second aspheric shape is then machined adjacent to the first. The axes, 26 and 27, of the two aspheric shapes, intersect at the same point 28 on the truncated side 23 of the cylinder 20 as shown in Figure 6. The very high degree of concentricity and accuracy needed is therefore achieved.

The truncated cylinder 20 is now turned over to machine other flat surfaces onto it. These two surfaces, the entrance surface 6 and the detector surface 8, are perpendicular to the respective axes, 26 and 27, of the two aspheric shapes which are, namely, the collimating surface 12 and the focusing surface 13.

In Figure 1, the diffraction grating surface 7, is machined in a final step. The grating surface 7 is flat and positioned on the front side 3 with the detector surface 8 and the entrance surface 6, but the grating surface 7 is tilted with respect to the other two surfaces 6 and 8 as shown in Figure 1.

Reflective coatings, 18 and 19, are applied respectively to the aspheric surfaces, 12 and 13, for reflectivity. The coating used may be gold or other similar reflective material.

A commercial diffraction grating (not shown) may be applied to the grating surface 7 in Figure 1, or the grooves 15 may be machined into the grating surface 7.

The machining method is preferably performed with diamond turning precision machining, which is performed in a humidity-controlled environment to achieve extreme tolerances and accuracy.

With respect to the above description then, it is to be realized that the optimal dimensional relationships for the parts of the invention to include variations in size, materials, shape, form, function and manner of operation, assembly, and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention.

Therefore, the foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and

operation shown and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

What is claimed is:

1. A monolithic spectrometer, comprising a unitary body of material, having:
(a) an entrance surface;
(b) a collimating surface:
(c) a grating surface;
(d) a focusing surface; and
(e) an imaging surface;
said entrance surface for receiving light rays and admitting said light rays into said monolithic spectrometer and directing said light rays to said collimating surface; said collimating for receiving said light rays from said entrance surface, making said light rays parallel and directing said light rays to said grating surface; said grating surface for receiving said light rays from said collimating surface, reflectively diffracting said light rays and directing said light rays to said focusing surface; said focusing surface for receiving said light rays from said grating surface, and focusing and directing said light rays to said imaging surface; and said imaging surface for receiving said light rays from said focusing surface and spectrally analyzing said light rays.

2. A monolithic spectrometer as recited in Claim 1, further comprising:
(a) a front side for locating said entrance surface and said grating surface and said imaging surface; and
(b) a back side in opposition to said front side, said back side for locating said collimating surface and said focusing surface.

3. A monolithic spectrometer as recited in Claim 1, wherein said material is optically homogeneous.

4. A monolithic spectrometer as recited in Claim 1, wherein said surfaces have a finish of sufficient quality to yield a system with a signal-to-noise ratio of at least 10:1.

5. A monolithic spectrometer as recited in Claim 1, wherein said collimating surface further comprises a finish of below 30 angstroms root mean square.

6. A monolithic spectrometer as recited in Claim 6, wherein said collimating surface further includes a reflective coating.

7. A monolithic spectrometer as recited in Claim 1, wherein said grating surface comprises a plurality of grooves per inch for diffracting light rays.

8. A monolithic spectrometer as recited in Claim 1, wherein said focusing surface further comprises a finish of below 30 angstroms root mean square.

9. A monolithic spectrometer as recited in Claim 9, wherein said focusing surface includes a reflective coating.

10. A monolithic spectrometer as recited in Claim 1, wherein said imaging surface further includes a detector material.

11. A monolithic spectrometer as recited in Claim 1, wherein said spectrometer has a total volume of less than 10 cubic inches of said material.

12. A method for making said monolithic spectrometer and other aspheric-based monolithic optical systems, comprising the steps of:

(a) machining a piece of material into a cylinder with a specified diameter, said cylinder having a first end and a second end;

(b) machining a wedge-shaped piece from said first end of said cylinder at a predetermined angle along a diameter of said first end of said cylinder, forming a truncated surface on one-half of said first end of said cylinder;

(c) machining a spherical surface on said second surface of said cylinder; and

(d) machining a plurality of aspheric optical surfaces, having intersecting axes, onto said spherical surface of said second end of said cylinder.

13. A method as recited in Claim 12 for manufacturing said monolithic spectrometer, further comprising the steps of:

(a) machining a wedge-shaped piece from said first end of said cylinder at a predetermined angle along a diameter of said cylinder, forming a truncated surface of one-half of said first end of said cylinder;

(b) machining said second end of said cylinder to a hemispherical surface;

(c) machining a first aspherical surface on said hemispherical surface of said second end of said cylinder;

(d) machining a cylindrical surface on said second end of said cylinder, said cylindrical surface forming around and concentric with said first aspheric surface;

(e) machining a second aspheric surface on said hemispherical surface of said second end of said cylinder, said second aspheric surface adjacent to said first aspheric surface, the center axes of both said first and second aspheric surfaces forming a plane through the center of said cylinder and intersecting at said focus points of said 1st and said 2nd aspheric surfaces and at said diameter representing the truncation line of said first end of said cylinder;

(f) machining a second cylindrical surface on said hemispherical surface of said second end of said cylinder, said second cylindrical surface forming around and concentric with said second aspheric surface;

(g) machining a flat surface on said first end of said cylinder; and

(h) machining a grating surface on said first end of said cylinder, said grating surface adjacent to said flat surface on said first end of said cylinder.

14. A method as recited in Claim 12 for manufacturing said monolithic spectrometer, wherein said material is selected from the group consisting of sapphire, polymethyl methacrylate, optical glass, zinc sulfide, zinc selenide, silicon and germanium.

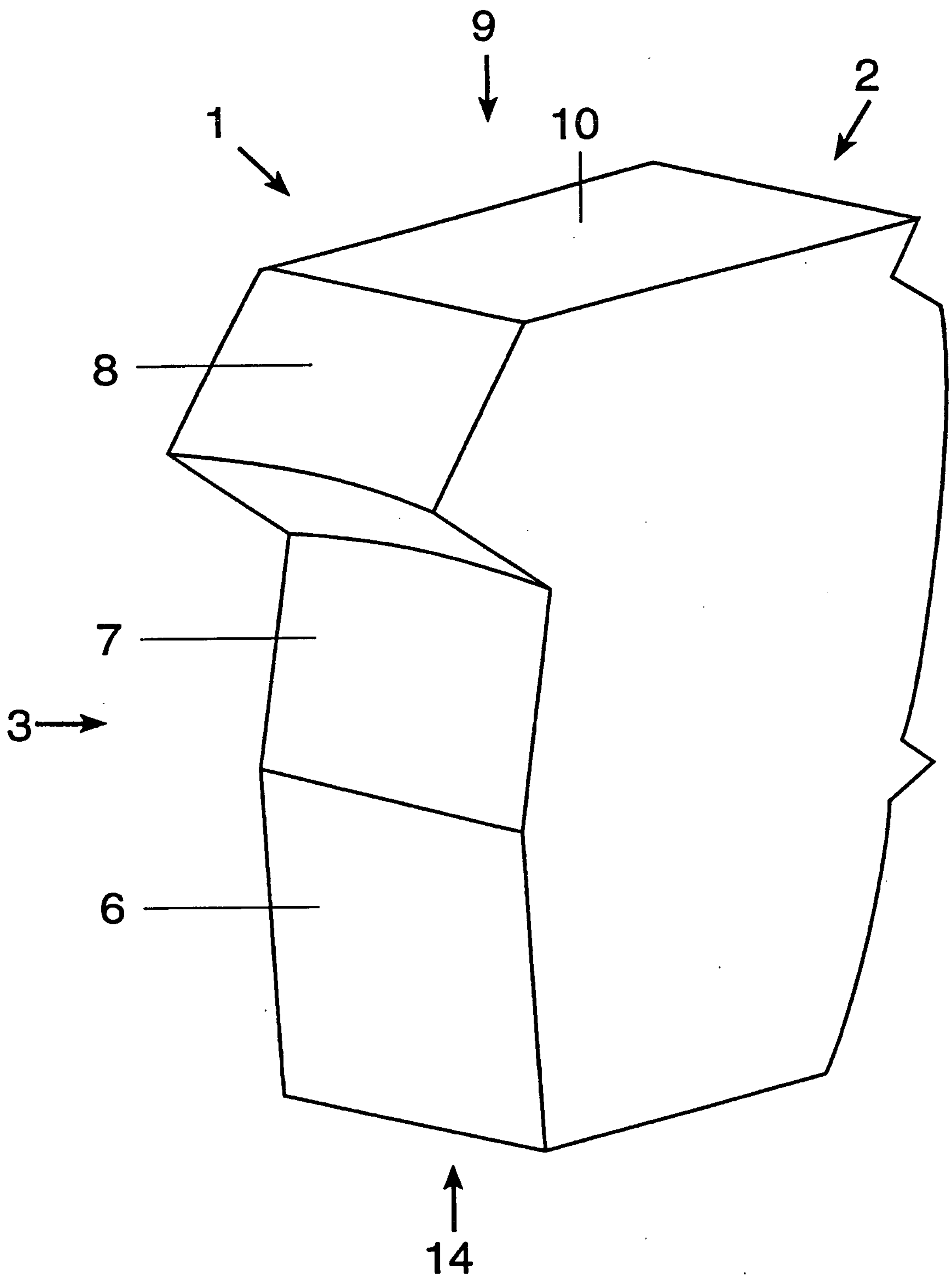

Figure 1

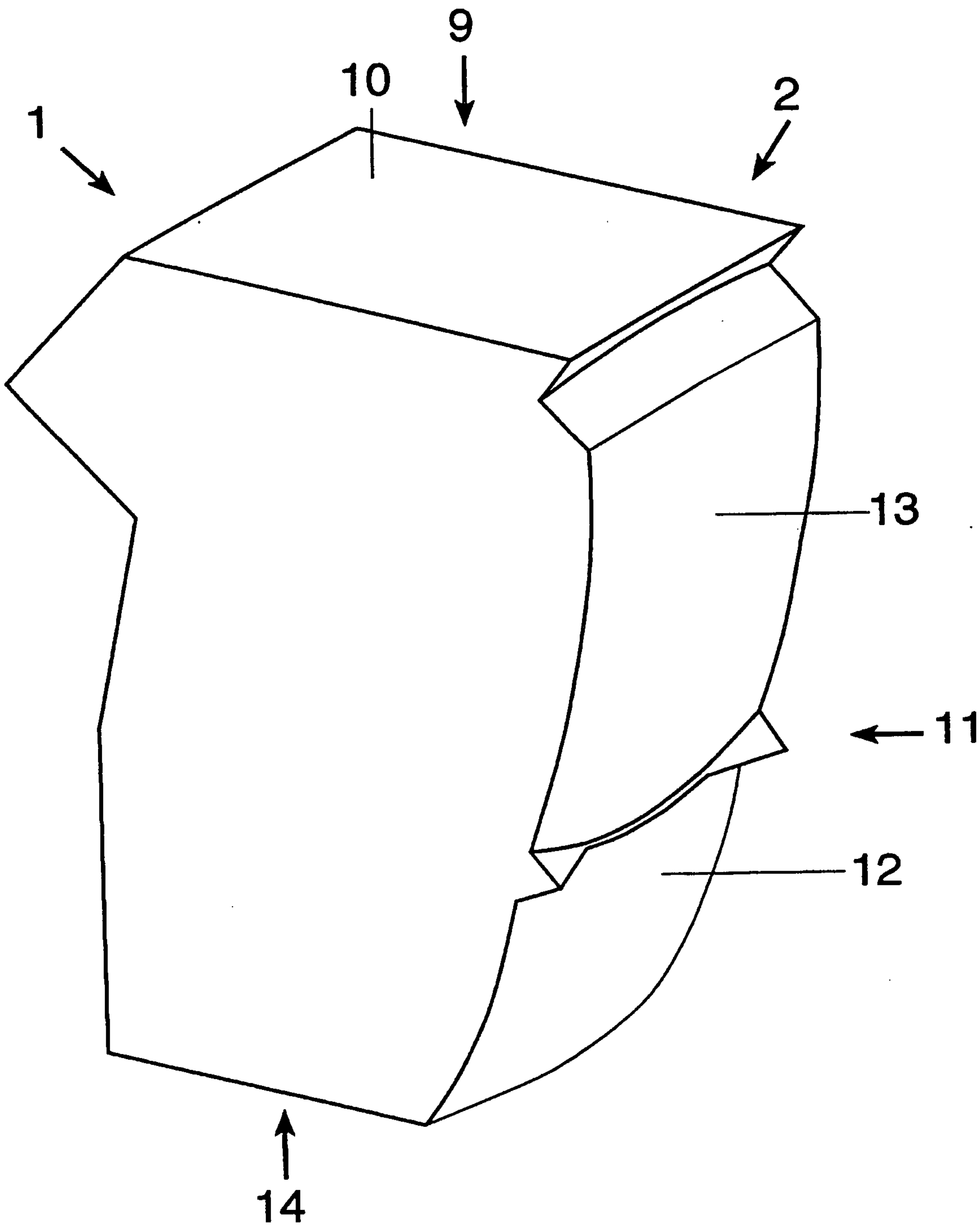

Figure 2

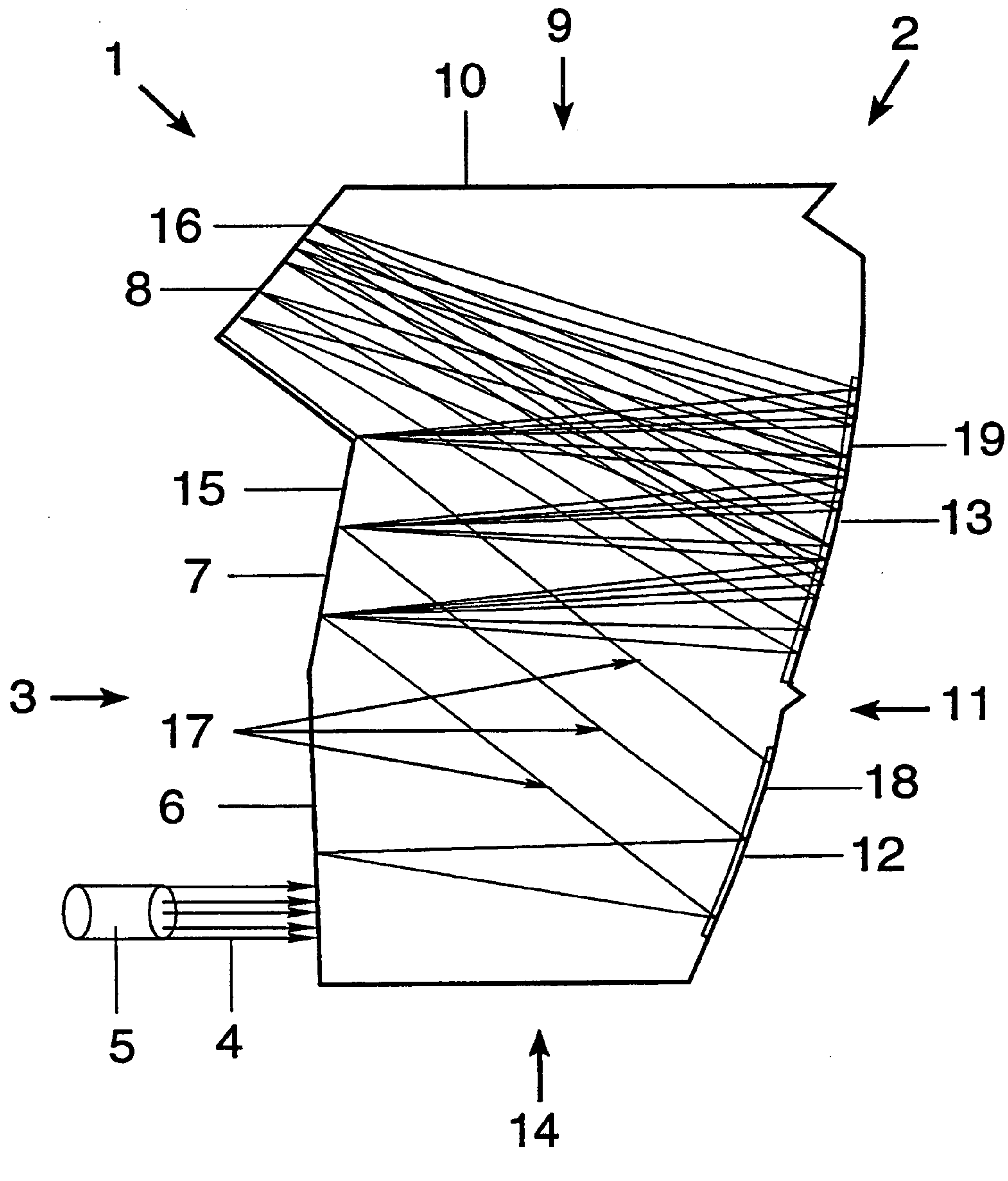

Figure 3

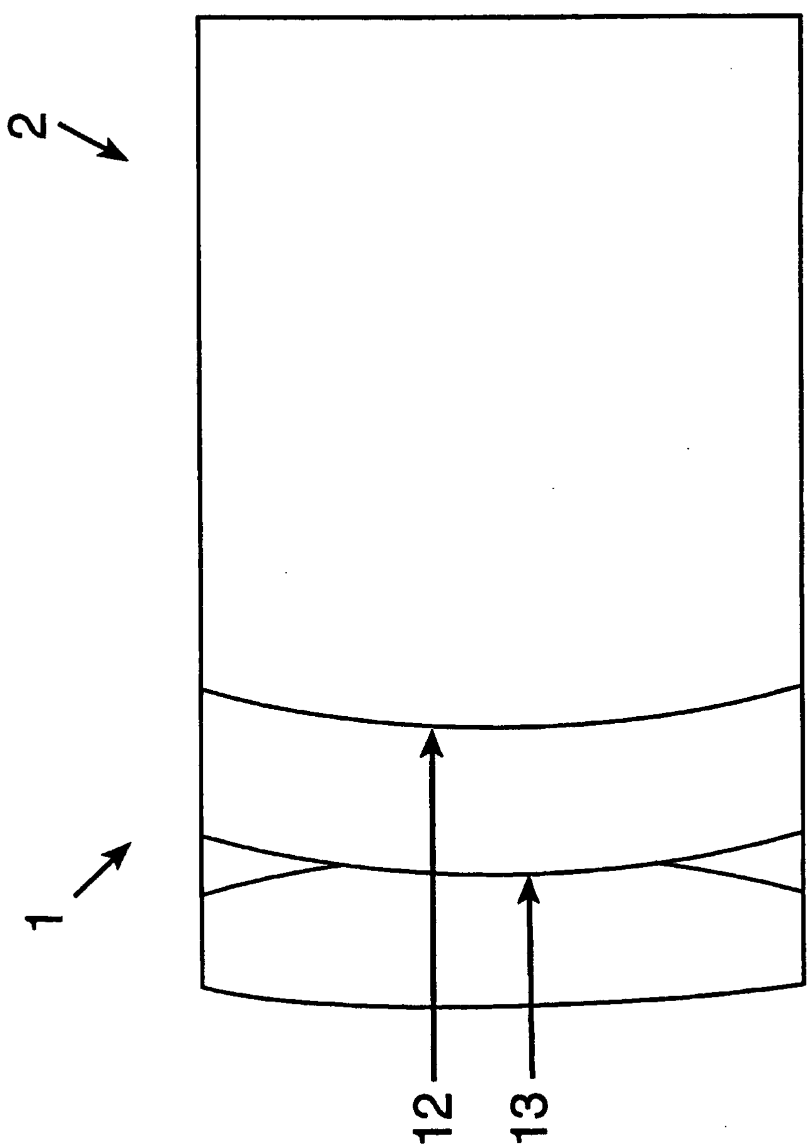

Figure 4

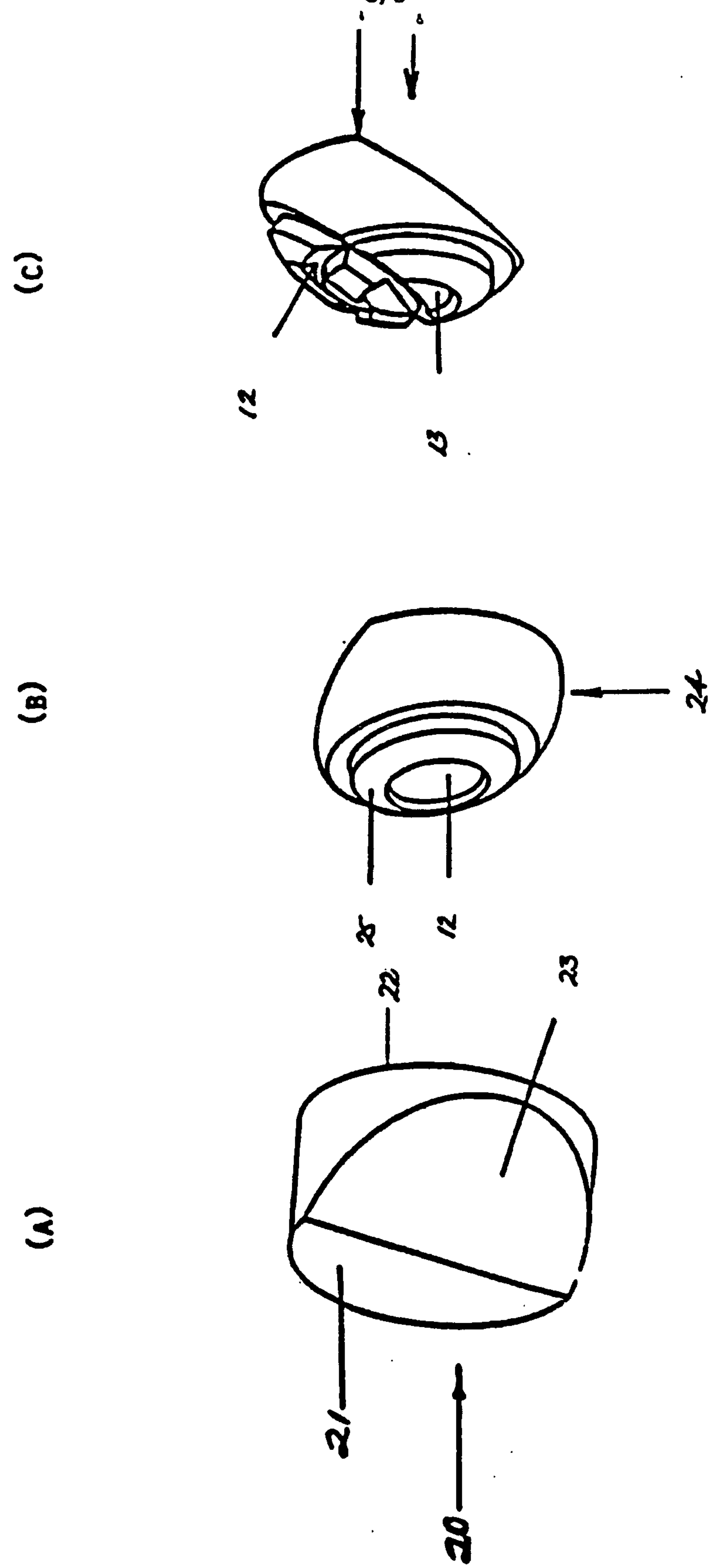

FIGURE 5

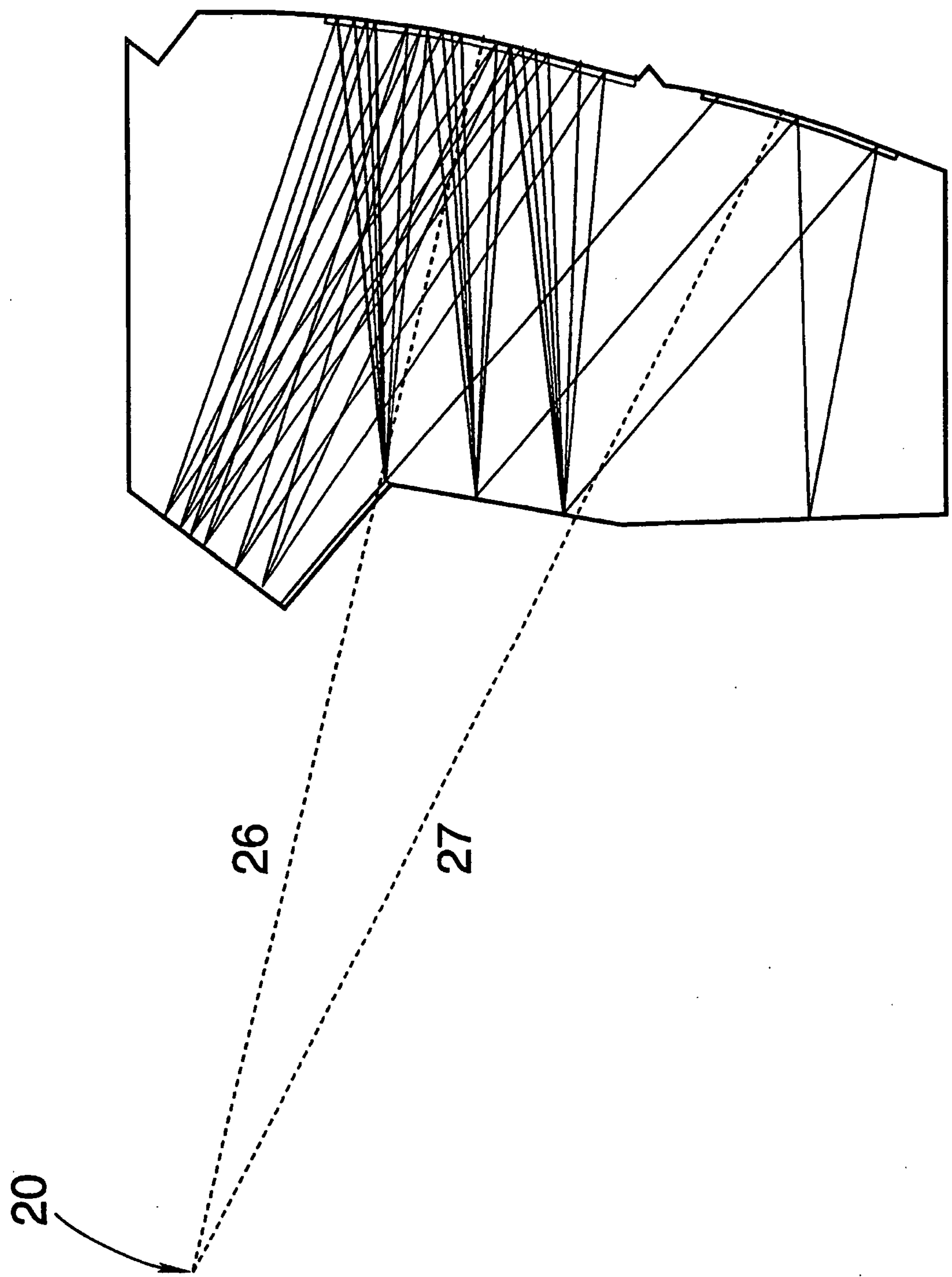

Figure 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/04369

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :GO1J 3/28
US CL : 356/328
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/328, 300,326,330-334; 385/37; 359/900

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US,A, 5,026,160(DORAIN ET AL) 25 JUNE 1991, SEE ENTIRE DOCUMENT	1-3, 6-7, 9, 10-11 --------- 4-5, 8
Y	US,A, 4,744,618(MAHLEIN) 17 MAY 1988,SEE ENTIRE DOCUMENT	12-14
A	WIPO,A,WO 92/11517(BERANEK ET AL)09 JULY 1992,SEE ENTIRE DOCUMENT	1-14
A	US,A,4,836,634(LAUDE) 06 JUNE 1989,SEE ENTIRE DOCUMENT	1-14

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Date of the actual completion of the international search	Date of mailing of the international search report
18 MAY 1996	23 MAY 1996

Name and mailing address of the ISA/US	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No.
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PHOTONIC SPECTRA,MAY 1994,"MONOLITHIC MINITURE SPECTROMETER-MMS 1",CARL ZEISS, SEE PAGE 91	1-14